

EXAMINING THE FEASIBILITY OF EXTINGUISHING ENGINE NACELLE FIRES BY THE STRATEGIC PLACEMENT OF INTUMESCENT MATERIALS

Ginger Bennett
Booz-Allen & Hamilton, Inc.

ABSTRACT

The objective of this program was to explore strategic placement of intumescent materials within the aircraft engine nacelle (AEN) for fire protection. Since the funding of this program was limited, an experimental evaluation was not allowable and only a literature review and manufacturer survey were performed. Intumescent materials respond to impingement of a fire by swelling and forming a protective char, to physically and thermally protect the coated structure. They have been used (or investigated for use) in various military platforms for all three services. Trade-offs must be made between the various features and requirements most important to the platform. The system can be engineered and problems designed around. This study showed the feasibility of utilizing strategic placement of intumescent materials within the AEN. For full exploitation of this technology, an experimental program is recommended. Justification for utilization of intumescent materials could be supported using a cost analysis.

BACKGROUND

AIRCRAFT ENGINE NACELLES

Aircraft engine nacelles (enclosures around the engine core) have fluid lines that are routed within the enclosure on the exterior of the machinery, to provide fuel, oil or hydraulic/brake fluid for the machinery (all of which are flammable). These enclosures/nacelles are typically ventilated with forced airflow, by a fan or by the free stream outside the aircraft, to prevent the accumulation of any flammable vapors, and to provide some cooling. In a typical fire scenario, one of the fluid lines leaks, and sprays or streams the flammable fluid onto the hot machinery, which results in a fire. The ventilation airflow continues to support the fire and directs the orientation of the resultant flame torch downstream. An automatic extinguishing system may be discharged from upstream to apply the extinguishing agent to the fire, but due to rapid dilution by the ventilation airflow and short residence time near the fire (and robustness of a bluff-body stabilized flame), many of these fires will not be extinguished with agent quantities permissible for many of these applications. Another concern is that the fire may reignite due to the fluid continuing to flow onto the hot surface with replenished airflow after the extinguishant has been drawn downstream. Because of these challenges, current engine nacelle applications have serious problems with fire events, and extinguishing techniques have only limited success, or require extinguishing quantities and hardware that are impractical because of size and weight. Other diverse techniques proposed to date to avoid the limitations of traditional extinguishing systems have been inadequate for many of these applications or have additional unacceptable disadvantages.

Many aircraft currently use firewalls at some location adjacent to engine nacelles to prevent fire propagation away from the engine. Unfortunately, these locations are usually limited to areas like the engine pylon (if the engine is mounted away from the aircraft body or wing), because it is desired to avoid constriction of the ventilation airflow directly around the engine under normal operating conditions. Such firewalls can also be heavy, and are only needed when an actual fire occurs and is near the site of the fire. The intumescent material design described here could provide such protection in a lightweight form at the location of the fire, without impeding the normal flow of air.

INTUMESCENT MATERIALS

Intumescence may be defined as "thermally induced expansion of a material." The popping of corn, expansion of perlite and vermiculite, and puffing of wheat, rice, and other grain cereals are common examples of intumescence. The pyrotechnic "snake" (fireworks) is another familiar example; the mixture

of sugar, oxidizer, and certain fuels generates a carbon char of highly expansive, voluminous, and friable nature. The mechanism of intumescence may be described as the rapid release of gas or vapor from a matrix which, upon rapid heating, undergoes a plastic or viscoelastic transformation that permits it to be expanded, inflated, or dilated by the expanding vapor or gas [1]. Intumescent materials come in several different forms, which include coating/paint, tape, caulk/ sealant, and putty. The char thickness may range from between 2 and 80 times that of the original material and result in an expansion amount from 1-30 in. The char thickness can be characterized by either high (>15), moderate (3 to 15), or low (<3) volume expansion. Intumescent coatings activate in a temperature range of 270 to 500 °F.

POTENTIAL APPLICATION IN THE AIRCRAFT ENGINE NACELLE

The intumescent coating can be applied as a very narrow and thin strip, in a form of one or more closed rings on the exterior of the machinery. These rings are positioned to swell against the enclosure at locations where clearance is minimal. If a fire occurred in an engine nacelle (such as due to a leak of flammable fluids onto hot exterior machinery components), the resulting flame would impinge onto a portion of the intumescent material, which would swell upon heating, normally several orders of magnitude beyond its original thickness. This swelling would block off the downstream airflow path in the vicinity of the fire, depriving it of a steady flow of oxygen and facilitating self-extinguishment. If the blockage is only partial, and the flame follows the re-directed airflow around the sealed-off area, the local intumescent-covered portion in that region would also swell, sealing off a perimeter of the machinery space and depriving oxygen flow until the fire self-extinguishes. In this manner, a series of "fire-walls" can be formed using a minimal quantity of intumescent. If an extinguishing system is also used, it can improve its effectiveness or permit smaller systems by weakening the fire and reducing the airflow dilution of the extinguishant. Previous analysis performed by the USAF suggested feasible application for machinery spaces (the concept having recently been submitted by the USAF for government patent protection, but not yet physically demonstrated).

The intumescent coating may only be needed in a limited region of the compartment, where the origin of fires is most likely. The intumescent material could also be mounted on the enclosure interior side, if it is deemed beneficial. If the gap is relatively large between the machinery and the enclosure, then a strip of coating may be placed on both the enclosure and machinery surfaces, which upon expansion could meet in the middle.

There is a need to find replacement extinguishing agents to the halons currently in use because production has been banned due to environmental concerns, but to date such replacement chemicals have shown reduced performance relative to halons. As a result, the Department of Defense is seeking additional design techniques that can assist in the performance of these replacement chemicals. This concept is ideal for this purpose because it weakens the flame due to oxygen starvation, and by restricting airflow increases its local concentration and residence time near the fire. This technique may be sufficient in many cases to permit the omission of an extinguishing system altogether.

Figure 1 is a cross-sectional view of the region between the exterior of a piece of hot machinery and the enclosure (or nacelle) that surrounds the machinery. The machinery exterior is hot enough to ignite fluids in this region, or ignition may occur near a source of electrical energy, such as a wire bundle or connection. The outer enclosure or nacelle is some distance from the heated machinery. In this example, a region chosen in proximity to a structural rib is illustrated. The clearance between the rib and machinery is commonly no more than 1-3 in. Other components may also be present or used as substitutes to the ribs that also result in local small clearances. They may be general enclosure contours, conduits, or other components. In addition, some components may be present on the machinery surface itself, which may reduce the clearance with the enclosure. An intumescent coating could be applied in the form of a

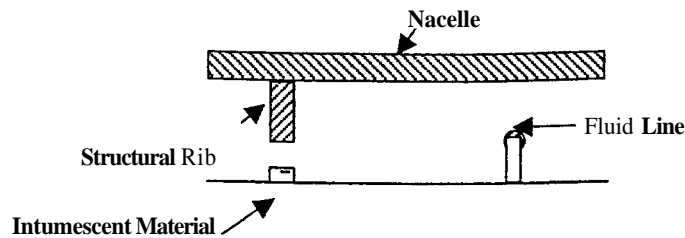


Figure 1. Cross-section view of region between nacelle and hot machinery.

narrow strip onto the machinery surface, or the components attached on it, in the region of reduced clearance. This region is just downstream of a location where a fluid line is mounted. Intumescent materials expand greatly in size when impacted by a flame or extreme heat, forming a carbonaceous structure, possibly with an outer char layer, to form an effective thermal barrier against extreme fire conditions, and are widely used in many applications. Intumescent materials come in several different forms that include coating/paint, tape, caulk/sealant, and putty. The char thickness may range from between 2 and **80** times that of the original material and result in an expansion amount of 1-30 in. The char thickness can be characterized by either high (>15), moderate (3 to 15), or low (<3) volume expansion.

As illustrated in Figure 2, the fluid line may have a leak, which would result in sprayed or leaking fluid that could ignite on or near the hot surface. The flame would thus orient itself downstream in the direction of ventilation airflow. Such a flame would impinge upon the strip of intumescent material placed downstream. Upon impingement, the intumescent material would expand, thereby forming around the rib or component above it and blocking off the flow of air locally. Such a local fire block would weaken the fire due to oxygen starvation (by preventing airflow in that direction) and possibly extinguish it.

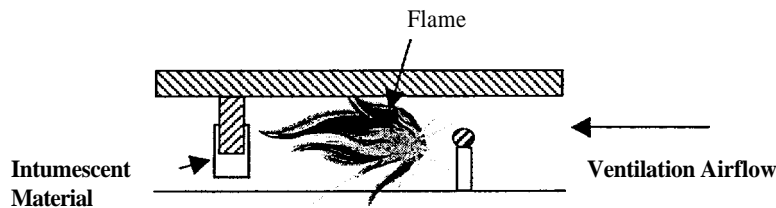


Figure 2. Fluid leak and subsequent fire.

CURRENT APPLICATIONS OF INTUMESCENT MATERIALS

Intumescent materials have been used (or investigated for use) in various military platforms for all three Services. Literature sources were reviewed, and the following applications, protected areas, and uses were found (Table 1). Intumescent materials have been used (or investigated for use) in various commercial applications. Literature sources were reviewed, and the following applications, protected areas, and uses were found (Table 2).

OBJECTIVE

The objective of this program was to explore a novel approach to engine nacelle fire protection using strategic placement of intumescent materials within the ventilated aircraft engine nacelle. Since the funding of this program was limited, an experimental evaluation was not feasible. Therefore, the purpose of this study was to evaluate the potential application of intumescent materials in an aircraft engine nacelle environment by reviewing existing literature and surveying various manufacturers.

TABLE 1. MILITARY PLATFORMS.

Application	Protected Areas	Uses
Aircraft	Fuel tanks, fire zone bulkheads, military ordnance, stored munitions, dry bays, self-sealing fuel lines, cockpit	Thermal barriers, insulators, prevent burnthrough, prevent toxic fume, smoke, and fire penetration
Ships (aircraft carriers)	Fire zone bulkheads, aircraft fuel tank spillage, military ordnance	Thermal barriers, insulators, prevent burnthrough, prevent toxic fume, smoke, and fire penetration
Submarines	Fire zone bulkheads, military ordnance	Thermal barriers, insulators, prevent burnthrough, prevent toxic fume, smoke, and fire penetration

TABLE 2. COMMERCIAL APPLICATIONS.

Application	Protected Areas	Uses
Aircraft	Fire zone bulkheads, military ordnance, stored munitions, dry bays, self-sealing fuel lines, cockpit, engine struts	Thermal barriers, insulators, prevent burnthrough, prevent toxic fume, smoke, and fire penetration, crashworthiness, structural integrity
Residential and commercial buildings	Doorways, vents, openings, steel	Prevent toxic fume, smoke, and fire penetration, structural integrity
Automobiles	Body panels separating the passenger compartment from the engine compartment, underbody, and the trunk compartment	Prevent toxic fume, smoke, and fire penetration, crashworthiness
Off-shore oil platforms	Metal structures and fuel valves	Protect flammable materials

APPROACH

Approximately 30 reports/papers were reviewed; the relevant data gained included the following:

- definition
- activation temperature
- methods to increase char strength
- issues (toxicity, heat exposure, fragility of char, installation, humidity)
- applications (military and commercial)
- protected areas
- uses
- hazards protected against

Approximately **80** manufacturers were reviewed, downselected, and divided into three intumescent categories (tapes [9 manufacturers], coatings [14 manufacturers], and caulks [9 manufacturers]).

Relevant data gained from this survey included the following:

- expected expansion factor and resulting expansion amount based upon original thickness
- durability of the coating
- adhesiveness and vibration-resistance of the expanded char following activation by fire
- physical properties of the expanded char
- activation temperature
- intumescent forms

ANALYSES CONDUCTED

The following analyses **were** conducted using a notional aircraft: (1) weight impact due to addition of intumescent material; (2) resistance of intumescent material to airflow environment; and (3) reduction in suppressant required due to presence of intumescent material.

SYSTEM CONFIGURATION DATA

Current aircraft engine nacelle configuration data were obtained and used for the physical and functional limitations of these intumescent systems. These data included aircraft operating conditions, engine materials, and areas of minimal clearance and other dimensional data. These data were used to examine the application of intumescent materials to a notional fighter aircraft.

OPERATING CONDITIONS

The following sources (compiled in Table 3), were used to select operational conditions for this notional aircraft examination application.

- “Halon Replacement Program for Aviation, Aircraft Engine Nacelle Application, Phase I—Operational Parameters Study” [2]
- Next-Generation Fire Suppression Technology Program (NGP) Element 1A (“Fires Experienced and Halon 1301 Fire Suppression Systems In Current Weapon Systems”) [3]
- “Halon Fire Protection Systems for Aviation—Existing System Configuration and Operational Environment Specifications” [4]
- “Fire Suppression System Performance of Alternative Agent in Aircraft Engine and Aircraft Dry Bay Simulations” [5]

TABLE 3. RANGE OF OPERATING CONDITIONS IN AIRCRAFT ENGINE NACELLE ENVIRONMENT.

Parameter	Minimum	Maximum
Air Pressure (psi)	1	14.7
Air Temperature (“F)	-65	630
Internal Air Flow (lb/s)	1.25	2.75
Surface Temperature (“F)	175	1300
Fire Initiation Temperature (“F)	540	790
Free Volume (ft’)	5	100

MATERIALS USED IN AIRCRAFT ENGINES

A brief review of structural and engine components was performed to identify potential material compatibility issues. These materials could be exposed to residual and combustion products in the post-deployment process. Some typical and future aircraft engine materials include titanium, aluminum, Inconel, stainless steel, titanium aluminide, silicon carbide fiber/silicon carbide ceramic matrix composite, and nickel aluminide.

CLEARANCE AND DIMENSIONAL DATA

A fighter and/or attack aircraft provides the most feasible platform to examine the implementation of intumescent materials due to the smaller clearance between the structural ribs and the engine core. The width of the (irregular) annular air passage is commonly no more than 2 to 6 in.

WEIGHT IMPACT

Many types of intumescent materials are currently in use. If one considers a strip 0.5 in wide, 0.12 in thick (to seal a clearance gap of 2 in or more) spread over an engine core of 36 in in diameter (which would represent an F-22 type engine), then a total volume of **0.00365 ft³** per ring would result. Accounting for the densities of the example product just mentioned, a weight 0.23 lbs per ring would exist. Even if four rings were used at various regions of the nacelle, a total weight of only 0.93 lbs would be added. This weight is minimal in comparison to the size of extinguisher systems currently in use, which can range from 10 to 20 lbs total weight per engine.

RESISTANCE TO AIRCRAFT OPERATING ENVIRONMENT

Without experimental results, it is difficult to determine accurately the response of the intumescent material to the aircraft operating environment because it is configuration and flight condition dependant.

However, the following methodology was employed to assess these characteristics:

- determine area of aircraft engine nacelle
- determine distributed load (pressure profile) using fluid mechanics (Ideal Gas Law, Continuity equation, and Bernoulli's equation)
- determine shear and normal stresses using mechanics of materials
- compare shear and normal stresses with manufacturer information

Determine Area of Aircraft Engine Nacelle

The equation for the area of a cylinder was used to determine the values of A_N, and A_C, (Table 4).

TABLE 4. PARAMETERS FOR AREA CALCULATION.

Parameters	Value
Nacelle Diameter (in)	52
Core Diameter (in)	36
Area _{nacelle} - A _N (ft ²)	14.75
Area _{rib} - A _r (ft ²)	10.56
Area _{core} - A _C (ft ²)	5.94
A _I = A _N - A _C (ft ²)	8.81
A _J = A _R - A _C - A _{INT} (ft ²)	≈ 0

Determine Distributed Load (Pressure Profile)

Next, the Ideal Gas Law, the Continuity equation, and Bernoulli's equation [6] along with the parameters in Table 5 were used to estimate the pressure profile on the expanded char. It is assumed that the dynamic pressures as a result of the airflow are the loading on the intumescent material. It is assumed that the velocity is the outside airflow velocity (approximately 700 mph). The resulting distributed load (pressure profile = p₂ - p₁) is 8.70 lbf/in².

Determine Normal and Shear Stresses

Next, equations in mechanics of materials were used to estimate the normal and shear stresses on the expanded char [6]. The expanded intumescent material was represented as a cantilever beam.

TABLE 5. PARAMETERS FOR DISTRIBUTED LOAD CALCULATION.

Parameters	Symbol	Value
Pressure (lb/ft ²)	P	---
Density (lb/ft ³)	ρ	0.04
Gas constant (ft-lbf)/(lb-mole-R)	R_{bar}	1545
Gas constant for air = R_{bar}/MW (((ft-lbf)/(lb-mole-R))/ MW (lb/lb-mole))	R	53.33
Molecular weight _{AIR} (lb/lb-mole)	MW	28.97
Temperature (°F)	T	500
Temperature (R)	T	959.67
Internal mass flow rate (lb/sec)	Mdot	2.2
Volumetric flow rate (ft ³ /min)	Q	3191.5
Cross-section of area of flow (ft ²)	A	---
Average velocity of flow (Wsec)	V	---
Specific weight of air (lb/ft ³)	γ	0.077
Average velocity of the fluid at section 1 (ft/sec)	v_1	1026.67
Average velocity of the fluid at section 2	v_2	0
Acceleration due to gravity (ft/sec ²)	g	32.17
Vertical distance from a datum (potential energy) (in)	z_1, z_2	0

Compare Shear and Normal Stresses with Manufacturer Information

Finally, the values determined previously for normal and shear stresses were compared with the manufacturers' information given for the expanded intumescent material. Physical properties (including the char strength) of the various intumescent materials (tapes, coatings, and caulks) investigated during this study were collected. It is assumed that the data provided by the manufacturers is accurate and verifiable. It is unclear whether some of these values (particularly the tensile strength values) are of the unexpanded or expanded material. Further investigation needs to be performed to determine this.

REDUCTION IN SUPPRESSANT REQUIRED

An estimate was made of the reduction in suppressant needed as a result of using this technology. To accomplish this, the following three scenarios were examined and the results are given in Table 6: (1) inerting the full free volume (100 ft³); (2) two-thirds of the free volume (66 ft³); and (3) one-third of the free volume (33 ft³). The following assumptions were made to accomplish this estimate.

- Assumed the free volume has been sealed off by the expanded intumescent material and thus creating the three scenarios (full free volume [100 ft³], two-thirds of the free volume [66 ft³], and one-third of the free volume [33 ft³]).
- Treated the free volume as a total-flood application (no airflow) and determine the amount of agent needed to inert the fixed volume.
- Assumed that 6% by volume of Halon 1301 is required to inert the space.
- Utilized the following information: One mole of gas = 22.4 liters/gram-mole. The molecular weight of Halon 1301 is 148.91 gram/gram-mole.

Also calculated was the estimate of Halon 1301 from MIL-E-22285 (Table 7) required [7]. As evidenced by this table, the values calculated to inert the fixed volume are less than both the values calculated using MIL-E-22285 and the values used in a certified system.

TABLE 6. ESTIMATE OF HALON 1301 REQUIRED TO INERT FREE VOLUME.

AEN, ft ³	V, ft ³	6% V, ft ³	Halon 1301, l	Halon 1301, gram	Halon 1301, lb
Free vol	100	6	169.88	1129.34	2.49
2/3 free vol	66	3.96	112.12	745.36	1.64
1/3 free vol	33	1.98	56.06	372.68	0.82
APU, ft ³	V, ft ³	6% V, ft ³	Halon 1301, l	Halon 1301, gram	Halon 1301, lb
Free vol	5	0.3	8.49	56.47	0.12
2/3 free vol	3.3	0.198	5.61	37.27	0.08
1/3 free vol	1.65	0.099	2.80	18.63	0.04

TABLE 7. ESTIMATE OF HALON 1301 FROM MIL-E-22285.

AEN, ft ³	V, ft ³	Halon 1301, lb	Halon 1301, lb	Halon 1301, lb	Halon 1301, lb	Halon 1301, lb
		W=0.05V	W=0.02V+0.25Wa	W=3(0.02V+0.25Wa)	W=0.16V+0.56Wa	Calculated From Inerting (Table 6)
		Rough nacelle/ low airflow	Rough nacelle/ low airflow	Rough nacelle/ high airflow	Deep frame nacelle/ high airflow	
Free vol	100	5.00	2.55	7.65	17.232	
2/3 free vol	66	3.30	1.87	5.61	11.792	1.64
1/3 free vol	33	1.65	1.21	3.63	6.512	0.82
Free vol	5	0.25	0.65	1.95	2.032	0.12
2/3 free vol	3.3	0.17	0.616	1.848	1.76	0.08
1/3 free vol	1.65	0.08	0.583	1.749	1.496	0.04

All of these engine nacelle systems are “certified” or approved in a given design configuration for a particular fire zone application and aircraft. The current specifications for Halon 1301 require a minimum of 6% concentration by volume in air be present simultaneously at all points in the engine nacelle for a minimum of 500 ms [3]. Therefore, to obtain this simultaneous concentration at several points (typically 12), additional Halon 1301 is added to ensure the system fully meets this requirement. It was also evidenced that the intumescent material reduces the required amount of Halon 1301. However, experimentation is needed to verify these calculations.

CONCERNS AND POTENTIAL RESOLUTIONS

Application of intumescent materials in the aircraft engine nacelle causes some concerns that must be recognized and accommodated. However, these can be designed and engineered around. The main concerns uncovered in this investigation were the following: potential toxicity, fragility of char, response in a high humidity environment, installation in highly cluttered areas, early expansion due to low activation temperature. Each concern uncovered was addressed with a potential resolution developed during this investigation.

CONCLUSIONS

Intumescent materials have properties that can positively or negatively influence its effectiveness for fire suppression (e.g., original thickness, expansion factor/amount, density, protection hours, activation/maximum temperature, forms, char characteristics, etc). Trade-offs must be made depending upon the requirements most important to the platform. The system can be engineered and problems designed around.

This study showed the feasibility of utilizing strategic placement of intumescent materials within the ventilated aircraft engine nacelle to reduce the amount in suppressant needed.

RECOMMENDATIONS

For full exploitation of this technology, an experimental program is recommended. Justification for use of intumescent materials is recommended and could be investigated via a cost analysis.

EXPERIMENTAL VALIDATION

Recommendations for a potential test program were developed as a result of this effort. It is recommended that a proof-of-concept test program be performed first, followed by a full-scale test program.

A test plan would be developed to determine whether sufficient blockage would occur from the intumescent swelling to reduce the sustaining airflow rate below which fires can be supported. Various compartment clearance widths, intumescent types and thicknesses, fire types, and ventilation airflow rates would be tested. Government laboratory equipment and facilities would be maximized to optimize use of resources. For the proof-of-concept program, the test apparatus would be a smaller scale version of generic engine bays and would be non-platform specific. The proof-of concept testing would consist of a few baseline tests (to validate conditions for a successful fire), tests with only the use of the intumescent coating, tests with only the use of the halon alternatives, and final tests to evaluate the synergistic effect of the intumescent coating and the halon alternative. A small-scale design matrix and would be constructed and contain compartment clearance widths, intumescent types and thicknesses, fire types, and ventilation airflow rates. Following the proof-of-concept program, this technology would be optimized and demonstrated in full-scale or aircraft test article.

COST ANALYSIS OF INTUMESCENT MATERIAL UTILIZATION

It is recommended that a cost analysis be performed to compare the existing Halon 1301 system and a system that utilized intumescent materials in conjunction with a less efficient Halon 1301 alternative. The net cost of the two fire suppression systems would be determined. This would be accomplished by determining system cost (which is a function of system size/weight) and the cost savings provided by the system (which are a function of extinguishant effectiveness and result in aircraft saved). The net cost is the cost of the system minus the cost savings.

Additional cost issues to consider include the following:

- The cost to clean the engine nacelle and core after utilization of the intumescent material should be investigated. To put this cost in perspective, the normal cost (man hours and equipment required) to clean the engine nacelle and core in post deployment of a Halon 1301 system should be determined.
- Maintenance costs to install the intumescent material could be estimated.
- The cost of employing the intumescent materials in conjunction with a less efficient Halon 1301 alternative could be estimated.
- The cost of using the intumescent material alone could be estimated.

The fire suppression system detailed cost element structure (CES) is based on the DoD 5000.4-M and MIL-HDBK-881 CES. It would be customized for this particular system and approach [8].

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